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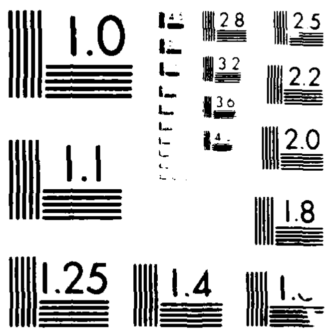

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Comparison of the Wall Pressure Fluctuations in Artificially Generated Turbulent Spots, Natural Transition, and Turbulent Boundary Layers

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Experiments have been conducted to measure the wall pressure fluctuations associated with artificially generated turbulent spots in a laminar boundary layer. The results show that both the rms wall pressure and the wall pressure spectra of turbulent spots are influenced by the local mean flow pressure gradient. The zero and favorable pressure gradient wall pressure data are in agreement with turbulent boundary layer results. However, the current spot data shows that, in the presence of an adverse pressure gradient, the spot's rms wall pressure is approximately 1.5-2.5 times larger than that found for the zero and favorable pressure gradient cases. These results are in general agreement with the adverse pressure gradient data of Huang and Hannan (1975). Additionally, the nearly constant magnitude of the spot's adverse pressure gradient wall pressure spectrum indicates a nearly even distribution of energy with frequency.

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COMPARISON OF THE WALL PRESSURE FLUCTUATIONS IN ARTIFICIALLY GENERATED TURBULENT SPOTS, NATURAL TRANSITION AND TURBULENT BOUNDARY LAYERS

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ABSTRACT

Experiments have been conducted to measure the wall pressure fluctuations associated with artificially generated turbulent spots in a laminar boundary layer. The results show that both the rms wall pressure and the wall pressure spectra of turbulent spots are influenced by the local mean flow pressure gradient. The zero and favorable pressure gradient wall pressure data are in agreement with turbulent boundary layer results. However, the current spot data shows that, in the presence of an adverse pressure gradient, the spot's rms wall pressure is approximately 1.5-2.5 times larger than that found for the zero and favorable pressure gradient cases. These results are in general agreement with the adverse pressure gradient data of Huang and Hannan (1975). Additionally, the nearly constant magnitude of the spot's adverse pressure gradient wall pressure spectrum indicates a nearly even distribution of energy with frequency.

NOMENCLATURE

B	Probability density function
C	Constant
d	Transducer diameter
f	Frequency
N	Frequency of occurrence
p	Wall pressure
$\overline{(p'^2)}^{1/2}$	RMS wall pressure
$\overline{(p'^2)}^{1/2}$	Mean value of rms wall pressure
q	Free stream dynamic pressure
R_x	Reynolds number $=U_\infty x/\nu$
t	Time
u′	Longitudinal turbulence intensity
U_∞	Free stream velocity
U_*	Friction velocity $=(\tau_w/\rho)^{1/2}$
x	Longitudinal coordinate
y	Vertical coordinate
β	Falkner-Skan parameter
δ_t	Boundary layer thickness
δ^*	Boundary layer displacement thickness
ω	Angular frequency
Φ	Wall pressure spectra
ρ	Density
τ_w	Wall shear stress
ν	Kinematic viscosity

INTRODUCTION

Knowledge of the wall pressure fluctuations beneath transitional and turbulent flows is required in order to understand and reduce aerodynamically and hydrodynamically generated noise. Measurements inside and outside turbulent boundary layers indicate that the wall pressure fluctuations generated by turbulence may well be the dominant mechanism in the generation of near field noise (self-noise). It is also known that panel vibration, for example, results from the spatial integration of the wall pressure field and its interaction with the structure's response function. Thus, if the wall pressure fluctuations are coupled with the vibratory modes of the structure, there will be a significant increase in the sound level radiated into the far field (for review articles see: Ffowes Williams, 1969; Willmarth, 1975).

Many detailed investigations have been performed on the fluctuating wall pressure beneath turbulent boundary layers utilizing both transducers mounted flush with the wall and those fitted with pinhole caps. From the research it has been determined that the energy associated with the turbulent wall pressure fluctuations is distributed over a wide frequency range with the major portion of the rms wall pressure magnitude arising from the convective range. It is also believed that the low wave number region may provide more effective excitation of structures than the convective region. Emmerling et al (1973) and Bull and Thomas (1976) have summarized the available experimental results, which show significant high frequency contributions to the pressure spectrum when the transducer size is reduced such that $dU_*/\nu < 100$. Their summaries and some more recent experimental results are reproduced in table 1 and figure 1.

In comparison to the turbulent boundary layer results, only a limited amount of data is available on the wall pressure fluctuations associated with natural transition and, more specifically, individual turbulent spots. The measurements of DeMetz and Casarella (1973) and Huang and Hannan (1975) have established certain statistical properties, in term of intermittency, of the wall pressure fluctuations during natural transition. It is not possible to infer individual spot properties from these measurements since the spots were occurring randomly and their measurements were made at uncontrollable locations within the spots. However, DeMetz and Casarella concluded that the magnitude of the intermittent wall pressure bursts during natural transition is approximately equal to the values measured in zero pressure gradient turbulent boundary layers. Also, the measurements of Huang and Hannan show that the rms wall pressure fluctuations occurring during natural transition, in the presence of a strong adverse pressure gradient, were 2-3 times larger than those found in a turbulent boundary layer. Finally, the recent wall pressure measurements by Johansson et al (1987) provide a comparison of the rms wall pressure measured in zero pressure gradient turbulent boundary layer ($(p'^2)^{1/2}/q=0.0078$) and in a turbulent spot ($(p'^2)^{1/2}/q=0.0094$).

The purpose of this paper is to report experimental data on the rms wall pressure fluctuations associated with artificially generated turbulent spots convecting in a laminar boundary layer. The spot data, for zero, favorable and adverse pressure gradients, will be compared to available wall pressure data in order to identify the relationship between the rms wall pressure fluctuations of a spot and that measured during natural transition and in turbulent boundary layers. Since wall pressure fluctuations are a direct measure of the surface excitation forces produced by the boundary layer, flow data of this type may be used to evaluate the vibrational and hydroacoustic responses of a structure.

MEASUREMENTS

The present measurements were made at a nominal free stream velocities of $U_\infty = 7.8$, 10 and 11 m/s in the closed-circuit wind tunnel of the Department of Applied Mechanics and Engineering Sciences at the University of California, San Diego. The flat plate on which the spots were generated and other experimental apparatus were the same as that used in some previous studies (Mautner and Van Atta, 1982; Mautner, 1983). The measured laminar boundary layer pressure gradients, as indicated by the Falkner-Skan parameter β, are given in table 2.

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The centerline turbulent spot data were obtained at longitudinal positions x=91.4, 121.9 and 152.4 cm downstream of the plate's leading edge. The wall pressure fluctuations were measured using a B&K model 4138 0.32 cm diameter condenser microphone whose sensing area was reduced by using a 0.8 mm diameter pinhole in the plate's surface. The microphone was connected to a B&K 2609 measuring amplifier. For each spot the wall pressure signature was represented by 2048 digital samples, the sampling being triggered by the spot generator (x=30.4 cm) signal. For the pressure record from each spot, the rms value $(p'^2)^{1/2}$ was calculated. Then for 500 values of $(p'^2)^{1/2}$, at a particular x location and pressure gradient, the mean value, $\overline{(p'^2)^{1/2}}$ was calculated. The values of the standard deviation were calculated for U_∞=10 m/s.

RESULTS AND DISCUSSION

The calculated values of the turbulent spot's rms wall pressure fluctuations are summarized in table 2, and the results for the three pressure gradients are indicated by the hashed area in figure 1. The results show that $(p'^2)^{1/2}/q$ for the zero and favorable pressure gradients are approximately equal to the values measured by "pinhole" transducers in zero pressure gradient turbulent boundary layers (table 1 and figure 1). The one exception, in the current results, is the zero pressure gradient data at x=121.9 cm, where the higher values of $(p'^2)^{1/2}$ are attributed to a slight variation in the pressure gradient along the flat plate. The experiments by Bull and Thomas (1976) resulted in the conclusion that wall pressure measurements made with "pinholes" are in error for $\omega\nu/U_\tau^2 \gtrsim 0.1$. The error in the wall pressure spectra would tend to reduce the "pinhole" data to that obtained by flush mounted transducers. Since the boundary layer parameters, such as wall shear stress, vary through the spot (Mautner, 1983) no corrections were applied to the current spot $(p'^2)^{1/2}$ data.

A direct comparison of the current zero spot pressure gradient data at x=152.4 cm and U_∞=10 m/s can be made with the spot wall pressure measurements of Johansson et al (1987). Johansson et al made their wall pressure measurements at x=154 cm and U_∞=10 m/s and obtained a $(p'^2)^{1/2}/q$=0.0094 which is in reasonable agreement with the current zero pressure gradient spot data. The magnitude of the current $(p'^2)^{1/2}/q$ for both zero and favorable pressure gradient spot data is in good agreement with the zero and favorable pressure gradient turbulent boundary layer results for equivalent values of dU_∞/ν. The nearly equal magnitude of the spot's $(p'^2)^{1/2}/q$ for both the zero and favorable pressure gradient is also in qualitative agreement with, for example, the results of Schloemer (1967). It should also be noted that both Wygnanski (1981) and Narasimha et al (1984), from their spot measurements, concluded that a favorable pressure gradient provides a stabilizing effect thus slowing down the growth and breakdown process associated with spots. Therefore, it may be the stabilizing effect of a favorable pressure gradient, in both transitional and turbulent flows, which contributes to the nearly equal $(p'^2)^{1/2}/q$ measured in both zero and favorable gradient flows. Finally, Johansson et al (1987) concluded from their turbulent boundary layer and spot wall pressure measurements that the mechanism generating the large wall pressure peaks, which in turn contribute to $(p'^2)^{1/2}$, appear to be the same in turbulent boundary layers and transitional flows.

However, when subjected to an adverse pressure gradient, the turbulent spot's rms wall pressure fluctuations are 1.5-2.5 times larger than either the zero or favorable pressure gradient results (table 2). The measured increases are in general agreement with the results of Huang and Hannan (1975). They found $(p'^2)^{1/2}/q \approx 0.038$ during natural transition on a forebody of revolution subjected to a strong adverse pressure gradient as compared to $(p'^2)^{1/2}/q \approx 0.015$ in a turbulent boundary layer with a mild, adverse pressure gradient. The increased $(p'^2)^{1/2}$ for the turbulent spot, and presumably for natural transition, is consistent with the larger velocity fluctuations (u') measured by Mautner (1983) in the adverse pressure gradient flow as compared to u' for a spot in a zero pressure gradient flow (for example, see Antonia et al, 1981). Higher velocity fluctuations were also measured by Schloemer (1967) and Burton (1973) in their adverse pressure gradient turbulent boundary layers. The 40% reduction in the spot's $(p'^2)^{1/2}$ from x=91.4 to 121.9 cm is due to the spot's adjustment to the constant pressure gradient region. This adjustment plus the subsequent 30% increase in $(p'^2)^{1/2}$ from x-121.9 to 152.4 cm indicate the sensitivity of the spot's $(p'^2)^{1/2}$ magnitude to the local mean flow pressure gradient.

For a boundary layer, Kraichnan (1956) formulated a qualitative relationship between the pressure and shear forces which states that the ratio of the rms wall pressure and the wall shear stress (τ_w) equals a constant, $(p'^2)^{1/2}/\tau_w$=C=6. Recent experimental results have determined that the constant C is on the order of 3 with typical values of 2.6 found by Willmarth and Roos (1965) and 3.4 by Blake (1970). For the current zero and favorable pressure gradient spot data, the ratio of the $(p'^2)^{1/2}$ values in table 2 and τ_w calculated using Prandtl's equation

$$(U_\tau/U_\infty)^2 = 0.0296\, R_{ex}^{-1/5} \qquad (1)$$

yield a range of values for C of 2.5-3.5. This calculation shows that both the zero and favorable pressure gradient spot data scale well with the wall shear stress and that the results are consistent with the zero pressure gradient turbulent boundary layer results. However, when the adverse pressure gradient spot $(p'^2)^{1/2}$ data are normalized by τ_w, a value of C=12 is obtained. In order to obtain C≈3, an unrealistic value of $U_\tau/U_\infty \approx 0.064$ would be required, indicating that the adverse pressure gradient spot data results do not scale with the local wall shear stress. A similar result was found by Burton (1973) for a turbulent boundary layer having an adverse pressure gradient. Additionally, wall shear stress measurements by Mautner (1983) for spot's in an adverse pressure gradient show values of U_τ/U_∞ = 0.033–0.038 at x=152.4 cm and u_∞=10 m/s. This compares to $U_\tau/U_\infty \approx 0.043$ calculated using Prandtl's equation.

Thus far the measurements for the wall pressure fluctuations associated with transitional and turbulent flows have been characterized by a single value of $(p'^2)^{1/2}$ which is representative of a mean flow condition. This method is satisfactory in characterizing the statistically steady properties of a turbulent boundary layer. However, the final stage of boundary layer transition is composed of randomly occurring spots, and previous measurements of $(p'^2)^{1/2}$ during transition have not identified the statistical distribution of the spot's $(p'^2)^{1/2}$ magnitude nor its relationship to the generation of acoustic noise.

To examine the variation of $(p'^2)^{1/2}$ about its mean value, plots of the frequency of occurrence N of a particular magnitude $(p'^2)^{1/2}$ as a function of $(p'^2)^{1/2}/\overline{(p'^2)^{1/2}}$ were constructed. For each pressure gradient and U_∞=10 m/s, the values of $(p'^2)^{1/2}$ from 500 spots at each x location were categorized using a 0.5 standard deviation bandwidth. The results in figures 2-4 show that, for each pressure gradient, the N distributions at each x exhibit excellent similarity. The N distributions for the zero and favorable pressure gradients (figures 2-3) are approximately equal and the $(p'^2)^{1/2}$ magnitudes are broadly distributed about the mean. In contrast, N distributions for the adverse pressure gradient (figure 4) show a 20-25% increase in the number of $(p'^2)^{1/2}$ values occurring at the mean and that the remaining $(p'^2)^{1/2}$ values are more concentrated about the mean. This character of the N distribution indicates that, even though $(p'^2)^{1/2}$ is a broadband property of the wall pressure field, the small variation in the magnitude of $(p'^2)^{1/2}$ in the adverse pressure gradient data would provide a stronger driving force on a structure which may result in higher self- and radiated noise levels.

The N distributions provide information about the variation of $(p'^2)^{1/2}$ over a large number of spots; however, they do not provide any information about the contribution of the spot's "random" wall pressure fluctuations in determining the value of $(p'^2)^{1/2}$. To examine this issue, probability density functions were calculated. For U_∞=10 m/s and each pressure gradient at x=152.4 cm, the probability density function for 500 spots were calculated and then averaged. The calculated probability density functions, B(p'), shown in figure 5 are given in terms of B(p')Δp', which represents the fraction of the total samples in the p' to p'+Δp' band (p' Δp'=0 occurs at $(p'^2)^{1/2}$). The results show that B(p') for all three pressure gradients are nearly equal and that small positive values of p' are more probable than small negative values of p'. It is this statistical nature of p' that not only results in the 1.5-2.5 increase in $(p'^2)^{1/2}$, but also, like the N distributions, indicates the presence of an intense wall pressure field during boundary layer transition under the influence of an adverse pressure gradient.

The calculated values of $(p'^2)^{1/2}$ and the N distributions provide broadband (in frequency) information about the turbulent spot. To obtain the distribution of energy with frequency, the spectra of the spot's wall pressure field were computed from the finite length, digitized time series p(t). For U_∞=10 m/s and each pressure gradient at x=152.4 cm, the spectra, Φ(f), for 100 spots were calculated and then averaged. The non-dimensional spectra are presented in figure 6. No corrections for the finite size of the transducer were applied to the spectra.

The spot's zero and favorable pressure gradient spectra (figure 6 a and b) are approximately equal and verify the nearly equal magnitudes of $(p'^2)^{1/2}$ given in table 2. These spectra are also in qualitative agreement with the turbulent boundary results of Blake (1970), Bull (1967) and Burton (1973) for a zero pressure gradient and Schloemer (1967) for a mild, adverse pressure gradient. The lower values of Schloemer's zero and favorable pressure gradient spectra are probably due to his larger transducer size and lower turbulent intensities.

For the adverse pressure gradient, the spot's wall pressure spectrum shows a nearly constant magnitude with frequency, which is in contrast to the rapid spectral decrease with increasing frequency found for both the zero and favorable pressure gradient spectra. Schloemer pointed out that the adverse pressure gradient spectrum for a turbulent boundary layer has a large magnitude, especially at lower frequencies, due to the increase in the longitudinal turbulent intensities (u') near the wall, y/δ_t<0.6. Similarity, the distribution of u' with y in the current spot data (Mautner, 1983) shows a higher level of u' throughout the central region as compared too the zero pressure gradient spot data of Antonia et al (1981), thereby producing the increased magnitude of $(p'^2)^{1/2}$ and its spectrum.

Lauchle (1978) has derived an expression for the acoustic efficiency of boundary layer transition and compared it to the acoustic efficiency of a turbulent boundary layer. He determined that the flow noise generated by transition is more efficiently radiated into the far field than the noise generated by a fully developed turbulent boundary layer (approximately 3 orders of magnitude in his example). At least for the current adverse pressure gradient spot data, the nearly constant magnitude of the spectra would indicate a greater possibility of the spot's wall pressure field coupling with both the structure and the propagating modes of the acoustic field to produce more intense near and far field noise levels.

SUMMARY

The current experimental results show that the magnitude of $(p'^2)^{1/2}$ and the spectra of the turbulent spot phase of boundary layer transition are strongly influenced by the local mean flow pressure gradient. The current spot data verifies the results of Huang and Hannan (1975) and shows that boundary layer transition in the presence of an adverse pressure gradient will result in $(p'^2)^{1/2}$ values which are approximately 1.5-2.5 times larger than that found for a zero or favorable pressure gradient. Additionally, the nearly constant magnitude of the spot's adverse pressure gradient spectrum indicates a nearly even distribution of energy with frequency.

The above results indicate that a transitional flow, when subjected to an adverse pressure gradient, will produce a stronger driving force on a structure over a wide frequency range. This condition may lead to a higher degree of coupling between the wall pressure field and the structure resulting in higher levels of both structure borne (self-noise) and fluid borne (far field) noise levels.

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Table 1. Measurements of Turbulent Boundary Layer Wall Pressure Fluctuations on Smooth Walls.

Investigator	U_∞ (m/s)	dU_τ/ν	$(p'^2)^{1/2}/q$ x10^3	Transducer Type	Pressure Gradient	Symbol Fig. 1
Willmarth & Roos (1965)	62	198	5.4	Flush	Zero	▶
		712	4.7			
Schloemer (1967)	24	101	5.2	Flush	Zero	○
	32	131	5.2			
	41	215	5.0		Mild Favorable	
	48	247	5.0			
	32	105	7.8		Mild Adverse	●
	44	141	7.8			
Bull (1967)	100	159	5.0	Flush	Zero	▽
		172	4.8			
Blake (1970)	22	45	10.6	Pinhole	Zero	×
Emmerling et al (1973)	8.5	18	10.9	Pinhole	Zero	
		47	9.3	Flush		
		202	5.3			
Bull & Thomas (1976)	24 - 36.3	47	6.8	Flush	Zero	□
		57	6.6			
		71	6.3			
		46	8.5	Pinhole	Zero	■
		57	8.1			
		70	7.7			
Burton (1973)	24	60	10.3	Pinhole	Strong Favorable	◇
	37	102	10.0			
	50	134	9.8			
	30	38	7.8-8.4*		Strong Adverse	
			8.0-10.0			
Huang & Hannan (1975)	46		15.0	Pinhole	Mild Adverse	
Schewe (1983)	6.3	19	9.8	Flush Measured	Zero	
		39	9.3			
		75	8.4			
		168	6.4			
		333	4.6			
		19	10.5	Flush Corrected	Zero	◆
		39	10.3			
		75	10.8			
		168	10.1			
		333	8.8			
Daniels & Lauchle (1986)	≈7	21	10.6	Flush	Zero	▼
		44	10.7			
Johansson et al (1987)	10	65	7.8	Flush	Zero	●

*Normalized by local q

Table 2. RMS Wall Pressure Fluctuations For Individual Turbulent Spots.

Pressure Gradient	x (cm)	U_∞(m/s)	β	$(p'^2)^{1/2}/q$ Mean	Standard Deviation
Zero	91.4	7.8	0.0	0.011	
	121.9	7.8	0.0	0.013	
	152.4	7.8	0.0	0.012	
	91.4	10.1	0.0	0.010	0.0005
	121.9	10.1	0.0	0.014	0.0009
	152.4	10.1	0.0	0.010	0.0005
Favorable	91.4	10.0	0.3	0.010	0.0005
	121.9	10.0	0.3	0.011	0.0005
	152.4	10.0	0.3	0.010	0.0005
Adverse	91.4	7.8	0.3	0.030	
	121.9	7.8	0.3	0.015	
	152.4	7.8	0.1	0.026	
	91.4	10.0	0.3	0.027	0.0011
	121.9	10.0	0.3	0.016	0.0004
	152.4	10.0	0.1	0.022	0.0006
	91.4	11.0	0.3	0.028	
	121.9	11.0	0.3	0.015	
	152.4	11.0	0.1	0.023	

$18 < dU_\tau/\nu < 30$

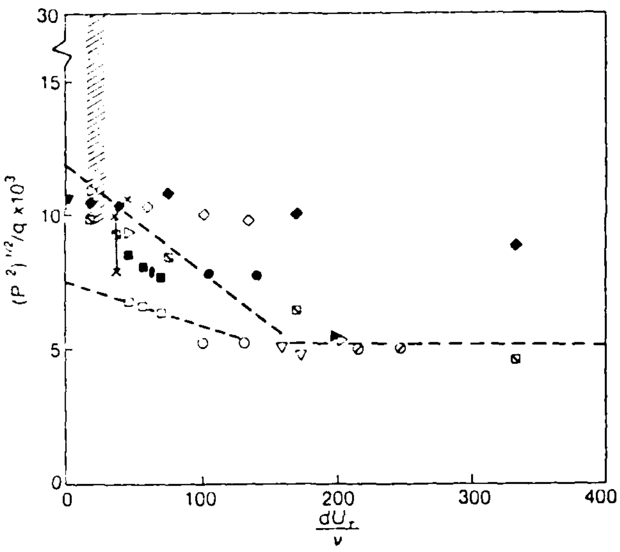

Figure 1. Variation of measured rms wall pressure fluctuations with transducer size and type. /// - Current data. See table 1 for additional symbols.

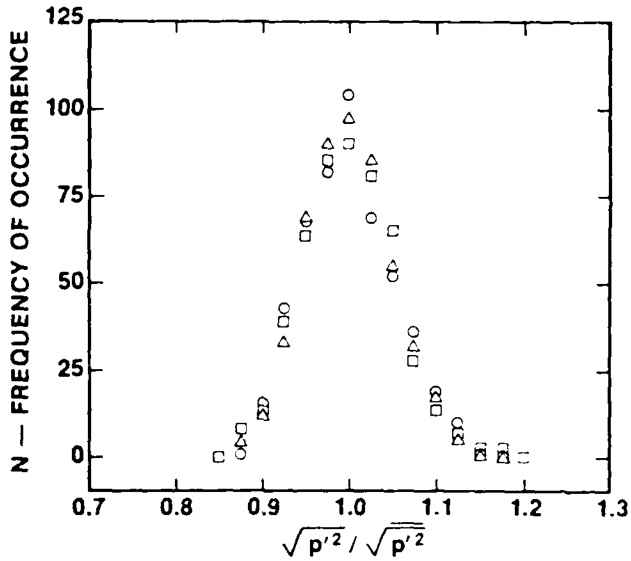

Figure 3. Frequency of occurrence distribution of rms wall pressure for 500 spots - favorable pressure gradient and U_∞=10 m/s. □ , x=91.4 cm; ○ , x=121.9 cm; Δ , x=152.4 cm.

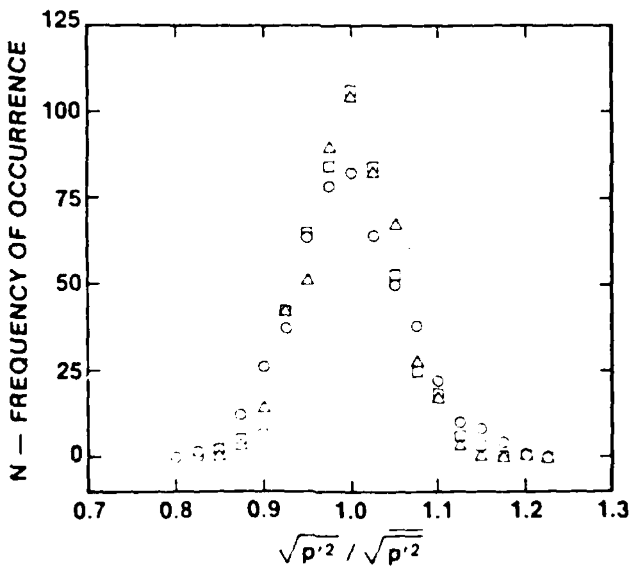

Figure 2. Frequency of occurrence distribution of rms wall pressure for 500 spots - zero pressure gradient and U_∞=10 m/s. □ , x=91.4 cm; ○ , x=121.9 cm; Δ , x=152.4 cm.

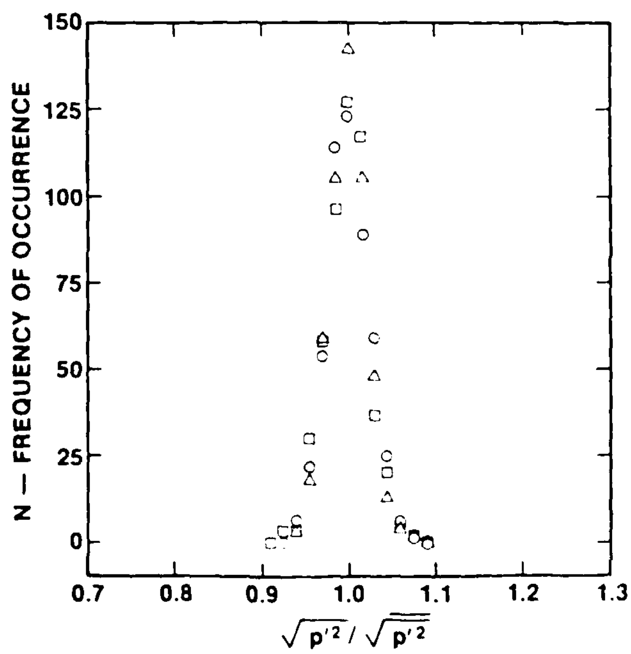

Figure 4. Frequency of occurrence distribution of rms wall pressure for 500 spots - adverse pressure gradient and U_∞=10 m/s. □ , x=91.4 cm; ○ , x=121.9 cm; Δ , x=152.4 cm.

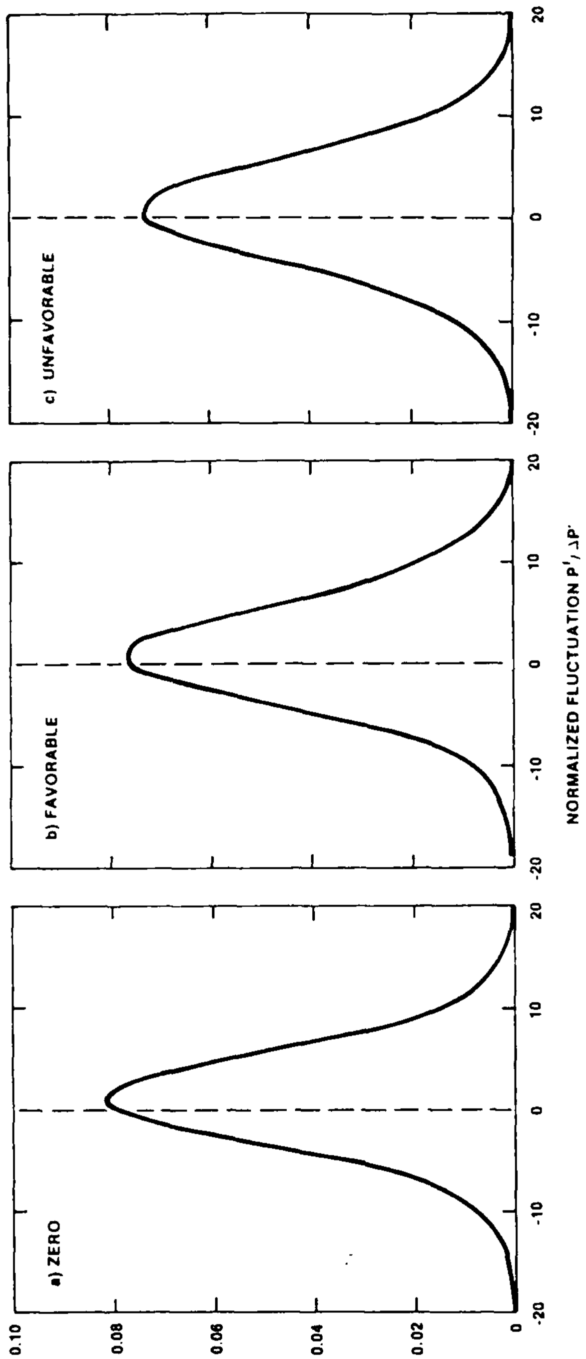

Figure 5. Probability density function of p′ . U_∞=10 m/s; x=152.4 cm; a) zero, b) favorable, and c) adverse pressure gradients.

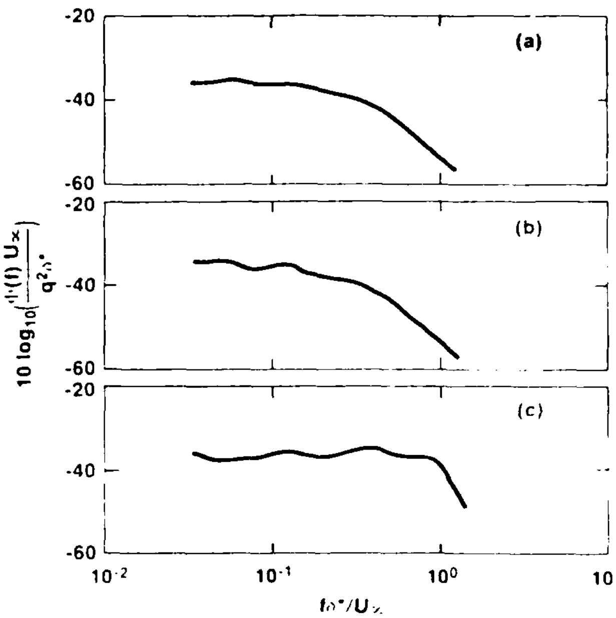

Figure 6. Comparison of the nondimensional power spectrum for a) zero, b) favorable and c) adverse pressure gradients.

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